WPS Team: Colors of Planets and Background Sources

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Colors of Earth-Like Exoplanets

- Primary global scale features that produce earth colors:

- Land vs Ocean vs Ice
- Clouds
- Atmosphere scattering & absorption

NASA "Blue Marble" from MODIS imagery
http://visibleearth.nasa.gov/view.php?id=57723

Colors of Earth-Like Exoplanets

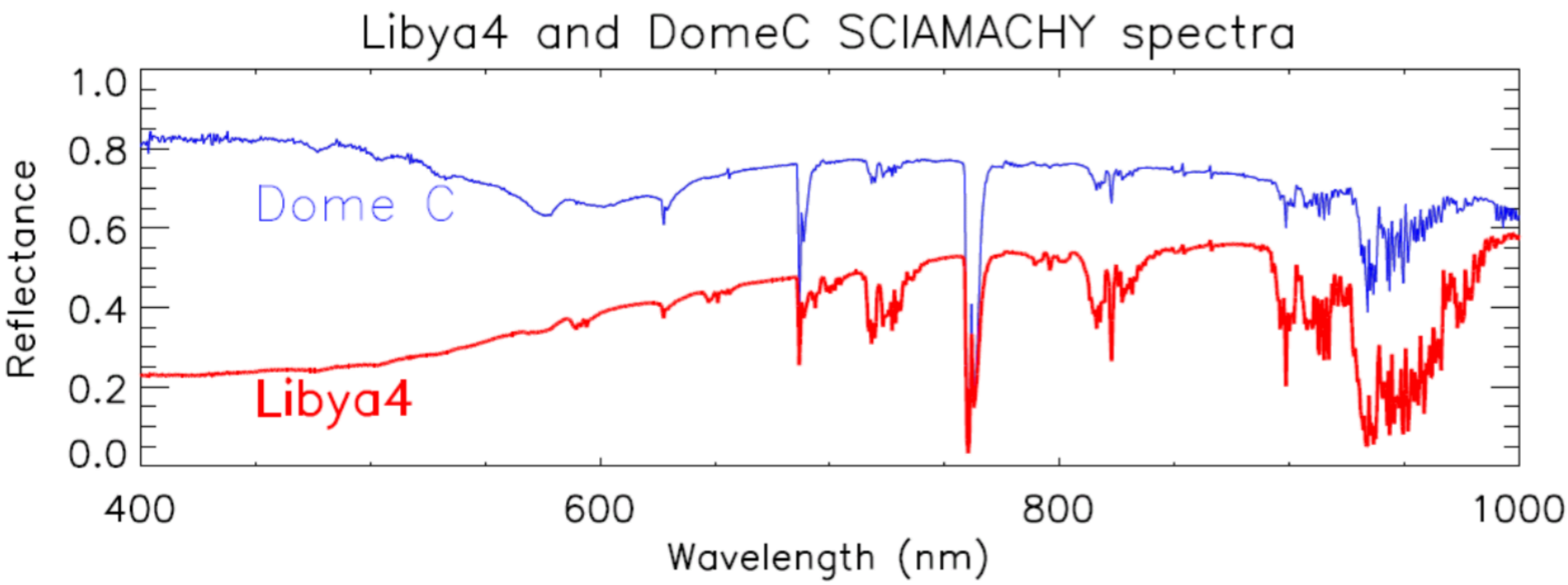
- Key physical characteristics relevant for WFIRST Coronagraph spectral range (400 – 1000 nm):
  - Spatial heterogeneity: land surface type, vegetation, ocean, cloud distribution
  - Angular variation: surface BRDF, cloud particle scattering phase functions
  - Spectral variation: surface spectral reflectance, absorption bands from important gases (O_2, O_3, H_2O, CO_2, CH_4), cloud particle extinction and scattering efficiencies
  - Polarization: molecular scattering, ocean surface glint, and clouds all introduce polarization signatures
- Goal to build a flexible simulation framework that represents all of these physical characteristics

Radiative Transfer inputs:

- Surface spectral reflectance
  - ASTER library (lab measurements)
  - Derived from Earth remote sensing data (SCIAMACHY)
- Surface BRDF models:
  - Cox-Munk for ocean, land surface model TBD
- Cloud particle scattering phase functions:
  - Mie theory for water droplets
  - Roughened Ice habit mixture models (Baum 2015)
- Gas absorption lines:
  - LBLRTM / HITRAN absorption line models

Aside: SCIAMACHY data

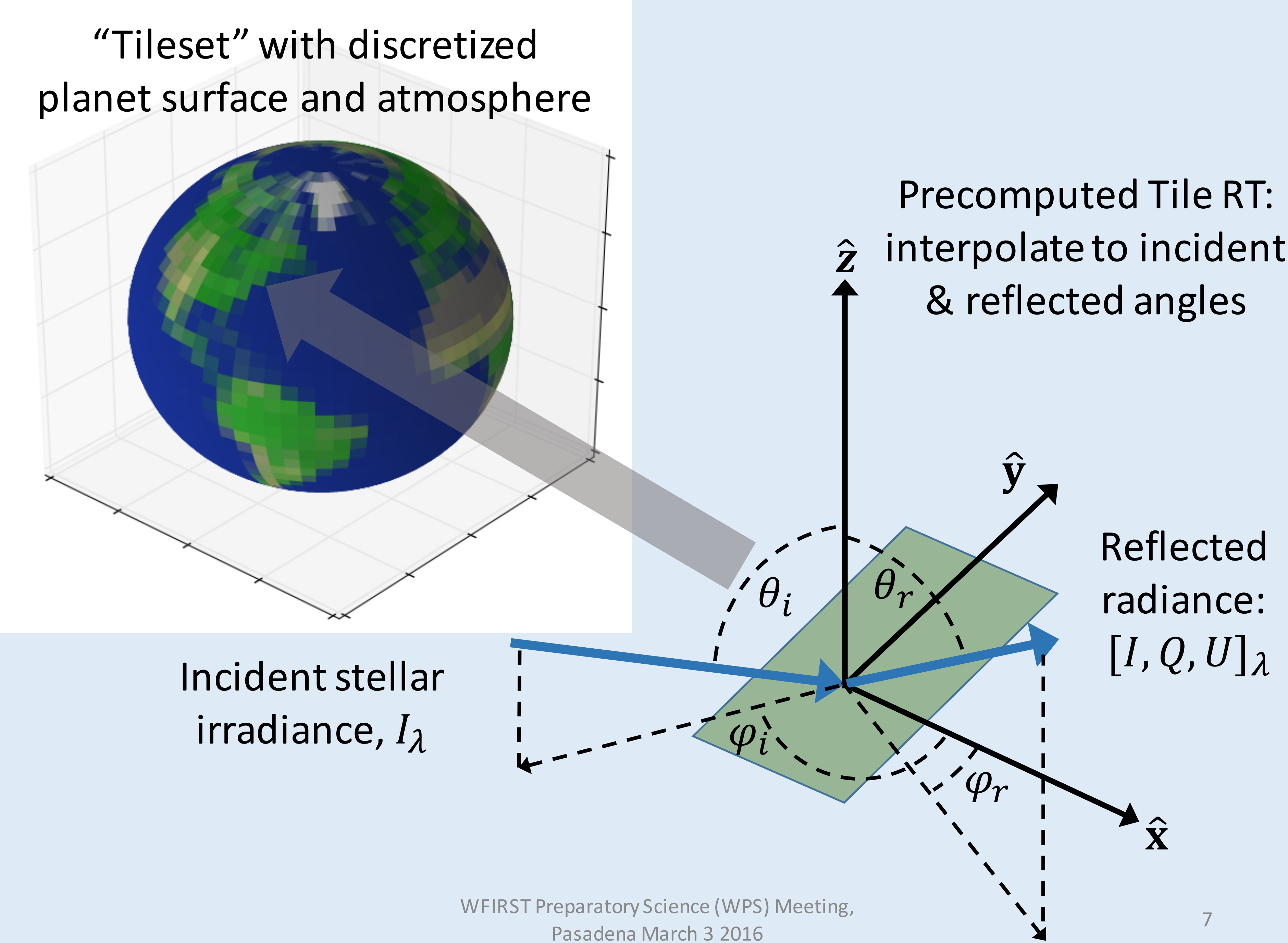
- Shortwave (300 – 2400 nm) spectrometer on ESA's ENVISAT mission, a Sun synchronous polar orbiter



X. Chen et. al., SPIE Proc vol. 9607, 2015

Simulation approach:

- Discretize planet surface via a set of “tiles”
- Precomputed radiative transfer (RT) for each tile can be interpolated to arbitrary observation geometry
- Simulate polarized reflectance at a relatively high spectral resolution, to allow simulation of arbitrary spectral bands, lower resolution spectra (IFS)
- Desire a flexible framework to allow many planet surface signatures to be compared within WFIRST coronagraph bands (or other future instruments)
- This general approach appears in many studies (e.g. VPL Earth Simulator, Robinson 2011, 2012, 2014; Fujii 2011; Sanromá 2013; …)


"Tileset" with discretized planet surface and atmosphere
Precomputed Tile RT: interpolate to incident & reflected angles
$\hat{z}$
$\hat{y}$
$\hat{x}$
θ_i
θ_r
φ_i
φ_r
Reflected radiance: $[I, Q, U]_\lambda$
Incident stellar irradiance, I_λ

Incremental development plan

1. No-atmosphere rock/ice planets
   a) Validate orbital and observation geometry
   b) Test Interface with EXOSIMs
2. Initial capability with simplified clouds, unpolarized reflectance (tile RT completed for this case)
3. Incorporate polarized RT model for tile RT
4. Generate “Earth-Twin” simulation; compare to published studies

Incremental development plan

5. Generate “Earth-like” simulations:
   a) Earth at other geologic epochs (e.g. Kaltenegger 2007)
   b) Tests of other published Earth-like signatures:
      a) Glint signature from liquid water
      b) Vegetation red-edge
      c) Vegetation BRDF
   c) Super Earths – need input from others modeling efforts for plausible compositions
      a) Increased surface pressure?
      b) Other atmosphere compositions? (Renyu Hu’s models)
   d) Other candidates of interest?